

Phase VI Glove Durability Testing

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The current state-of-the-art space suit gloves, the Phase VI gloves, have an operational life of 25 – 8 hour Extravehicular Activities (EVAs) in a dust free, manufactured microgravity EVA environment. Future planetary outpost missions create the need for space suit gloves which can endure up to 90 – 8 hour traditional EVAs or 576 – 45 minute suit port-based EVAs in a dirty, uncontrolled planetary environment. Prior to developing improved space suit gloves for use in planetary environments, it is necessary to understand how the current state-of-the-art performs in these environments. The Phase VI glove operational life has traditionally been certified through cycle testing consisting of International Space Station (ISS)-based EVA tasks in a clean environment, and glove durability while performing planetary EVA tasks in a dirty environment has not previously been characterized.

Testing was performed in the spring of 2010 by the NASA Johnson Space Center (JSC) Crew and Thermal Systems Division (CTSD) to characterize the durability of the Phase VI Glove and identify areas of the glove design which need improvement to meet the requirements of future NASA missions. Lunar simulant was used in this test to help replicate the dirty lunar environment, and generic planetary surface EVA tasks were performed during testing. A total of 50 manned, pressurized test sessions were completed in the Extravehicular Mobility Unit (EMU) using one pair of Phase VI gloves as the test article. The 50 test sessions were designed to mimic the total amount of pressurized cycling the gloves would experience over a 6 month planetary outpost mission. The gloves were inspected periodically throughout testing, to assess their condition at various stages in the test and to monitor the gloves for failures. Additionally, motion capture and force data were collected during 18 of the 50 test sessions to assess the accuracy of the cycle model predictions used in testing and to feed into the development of improved cycle model tables.

This paper provides a detailed description of the test hardware and methodology, shares the results of the testing, and provides recommendations for future work.

I. Introduction

The Phase VI Glove is currently certified to perform up to 25 – 8 hour shuttle or ISS based Extravehicular Activities (EVAs). However; future planetary outpost missions create the need for space suit gloves which can endure up to 90 – 8 hour traditional EVAs or 576 – 45 minute suit port-based EVAs in a dirty planetary environment. The Phase VI glove operational life has traditionally been certified through cycle testing consisting of International Space Station (ISS)-based tasks in a clean environment. Their durability while performing planetary EVA tasks in a dirty environment has never before been characterized.

Testing was performed to characterize the durability of the Phase VI Glove and identify areas of the glove design which need improvement to meet the requirements of future NASA missions. At the start of this testing, the Constellation Program (CxP) included plans for outpost missions on the lunar surface. Therefore, lunar simulant was used in this test to help replicate the dirty lunar environment. While the simulant used was specific to the lunar environment, the tasks performed during testing were generic planetary surface EVA tasks which are applicable to any planetary environment. The results of the testing were documented in a test report¹, and will be fed into the development of improved space suit gloves. This paper introduces the reader to the test hardware and methodology, details the results of the testing, and provides conclusions and recommendations for future work.

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II. Test Objectives

The primary objective of this effort was to conduct manned suited cycle testing on one pair of Phase VI gloves until the gloves failed, or met the number of cycles which would be accrued during a 6 month planetary outpost mission, in order to baseline the durability of the Phase VI gloves.

The secondary objective of the testing was to develop and either verify or recommend improvements to a planetary EVA cycle model table. The method used to estimate the number of cycles which would occur over a 6 month mission is described in the Test Plan Development section of this paper.

III. Test Plan Development

A. Initial Task List Development

While glove cycle testing has traditionally involved the repetition of shuttle or ISS based tasks in a clean environment, the goal of this test was to select tasks which were representative of what would be performed on a planetary surface. The tasks used in this test were chosen based on an examination of CxP lunar EVA operational concepts as well as historical Apollo EVA documentation. The Apollo EVA timelines were used to estimate the frequency of the performance of various tasks over individual EVAs, as well as a mission's worth of EVAs.

Initially two separate task lists and cycle model tables were developed, one for a mission containing 90 8-hr traditional EVAs, and one for a mission containing 576 45-minute suit port-based EVAs. At the completion of development, the suit port-based EVA cycle table had a greater number of total cycles than the traditional EVA cycle table, and was therefore used in this test as the worst case scenario. The suit port-based EVA cycle table development is presented in this section. The potential tasks identified, as well as their estimated frequency per EVA, and estimated frequency per crewmember over a 6 month increment, are defined in Table 1. A multiplier of 576 (total number of EVAs) was used to go from the number of times a particular task was

Table 1. Initial task list.

| Task | # times task performed per EVA | # times task performed per 6 mo. Increment (per CM) |
|--|--------------------------------|---|
| <i>Routine Non-Science Tasks</i> | | |
| Rover Joystick Ops | N/A | 30 |
| Suit umbilical connector demate/mate | 2 | 1152 |
| Suit port transfer module ops | N/A | 30 |
| Suit dust removal | 1 | 576 |
| Dismount/Mount Rover | 1 | 576 |
| <i>Maintenance Tasks</i> | | |
| Change tire on rover | N/A | 3 |
| Camera/light/window dust removal | N/A | 72 |
| <i>Science Tasks</i> | | |
| Sample Pick-up | 4 | 1152 |
| Sample Split Open | 2 | 576 |
| Scoop | 4 | 1152 |
| Drive Tube | 0.5 | 144 |
| Hammer | 0.5 | 144 |
| PIP Pin | 0.5 | 144 |
| Drive Tube | 0.5 | 144 |
| Rake | 1 | 288 |
| Trench | 0.25 | 72 |
| Carry sample carrier full of day's worth (16.7 kg) samples | 0.25 | 72 |
| Hand-held magnometer use | 1 | 288 |
| Deploy science station/packages | N/A | 2 |

performed per EVA to the number of times the task was expected to be performed during a six month increment. In cases where only one crewmember (CM) (out of a two person pair) was needed to perform a particular task, the total number of times the task was performed per six month increment was divided by two.

B. Pilot Testing and Final Task Selection

Once the initial task list had been developed, pilot testing was performed to create an estimate of wrist flexion/extension, wrist adduction/abduction, and finger flexion/extension cycles achieved per task, and to downselect to a final task list containing 5-10 repeatable tasks to be used in testing. A single cycle of each joint is defined as one flexion and one extension or one adduction and one abduction of the specified joint. Section 3.3.1 of the Anthropometry and Biomechanics Facility (ABF) Glove Durability Test Report¹ describes the criteria used in

Table 2. Pilot testing tasks and cycles.

| Task # | Task | Wrist Flex/Ext | Wrist Add/Abd | Finger Flex/Ext |
|--------|-------------------------------|----------------|---------------|-----------------|
| | <u>Selected Tasks</u> | | | |
| 1 | Fluid Connector (mate/demate) | 1.58 | 4.04 | 2.14 |
| 2 | Rock Pick-up (1x) | 2.06 | 1.88 | 1.04 |
| 3 | Joystick | 1.63 | 4.33 | 0.73 |
| 4 | Hammer (5x) | 2.75 | 5.75 | 1.51 |
| 5 | Brush (Object) (10x) | 7.7 | 17.7 | 1.85 |
| 6 | Shovel (Scoop) | 1.7 | 2.68 | 1.78 |
| 7 | Shovel (Hoe) - trench (10x) | 9.3 | 13.3 | 1.63 |
| 8 | Two Handed Grab | 0.35 | 2.19 | 1.03 |
| | <u>Deleted Tasks</u> | | | |
| 9 | Hand Rail | 0 | 0 | 1.10 |
| 10 | T-Handle (mate/demate) | 6.1 | 9.12 | 5.48 |
| 11 | PIP Pin | 0.63 | 2.23 | 1.23 |
| 12 | Drive Tube | 1.13 | 2.9 | 2.95 |
| 13 | Ratchet | 1.16 | 3.19 | 1.32 |
| 14 | Brush (Self) (10x) | 7.7 | 12.6 | 1.56 |

the software program to classify movement as a cycle.

During the pilot testing, 6 subjects performed a series of 15 tasks in an unpressurized, shirtsleeve environment while wearing a pair of Phase VI gloves equipped with motion capture markers. The ABF used the Vicon® motion capture system to capture the motions performed by test subjects during the pilot testing, and used the data collected to create a table of the average number of cycles seen per task, as well as the associated standard deviations. The standard deviations, along with engineering judgment, were used to downselect from 15 tasks to the 8 most repeatable tasks. These 8 tasks were chosen as the final tasks which would be used in the glove durability test. Table 2 contains a list of the 15 tasks performed during the pilot testing, as well as the average number of wrist flexion/extension, wrist adduction/abduction and finger flexion/extension cycles recorded for each task. The “selected tasks” are the tasks that were selected as the 8 final tasks to be performed in cycle testing.

C. Final Cycle Model

Once the pilot testing was complete, the data collected was fed back into the initial task list to determine the total number of cycles the gloves would see over a 6 month planetary outpost mission. Table 3 contains the total cycles for each task, as well as the total predicted cycles which would be seen over a mission. As noted in the table, the total cycles were doubled to attain a Factor of Safety (FOS) of 2. An expanded version of Table 3 containing all notes and assumptions made is located in Appendix F of the EVA Technology Development Project (ETDP) Phase VI Glove Durability Test Report.²

Table 3. Final cycle model.

| Task | # times task performed per EVA | # times task performed per 6 mo. Increment (per CM) | Total Wrist Flex/Ext Cycles | Total Wrist Add/Abd Cycles | Total Finger Flex/Ext Cycles |
|--|--------------------------------|---|-----------------------------|----------------------------|------------------------------|
| <i>Routine Non-Science Tasks</i> | | | | | |
| Rover Joystick Ops | N/A | 30 | 978 | 2598 | 440 |
| Suit umbilical connector demate/mate | 2 | 1152 | 7027 | 10506 | 2465 |
| Suit port transfer module ops | N/A | 30 | 11 | 66 | 31 |
| Suit dust removal | 1 | 576 | 22176 | 50976 | 5338 |
| Dismount/Mount Rover | 1 | 576 | 0 | 0 | 1271 |
| <i>Maintenance Tasks</i> | | | | | |
| Change tire on rover | N/A | 3 | 418 | 1148 | 476 |
| Camera/light/window dust removal | N/A | 72 | 2772 | 6372 | 667 |
| <i>Science Tasks</i> | | | | | |
| Sample Pick-up | 4 | 1152 | 2373 | 2166 | 1198 |
| Sample Split Open | 2 | 576 | 1584 | 3312 | 868 |
| Scoop | 4 | 1152 | 1958 | 3087 | 2054 |
| Drive Tube | 0.5 | 144 | | | |
| Hammer | 0.5 | 144 | 396 | 828 | 217 |
| PIP Pin | 0.5 | 144 | 91 | 321 | 178 |
| Drive Tube | 0.5 | 144 | 163 | 418 | 425 |
| Rake | 1 | 288 | 1071 | 1532 | 469 |
| Trench | 0.25 | 72 | 670 | 958 | 118 |
| Carry sample carrier full of day's worth (16.7 kg) samples | 0.25 | 72 | 25 | 158 | 74 |
| Hand-held magnometer use | 1 | 288 | 0 | 576 | 288 |
| Deploy science station/ packages | N/A | 2 | 43 | 173 | 86 |
| Total Cycles | | | 41756 | 85195 | 16664 |

IV. Test Plan Overview

This section provides an overview of the test plan and test procedures. In depth details specific to the test plan and procedures are located in the ETDP Phase VI Glove Durability Test Plan.³

A. Overview of Test Activities

Test activities began with the performance of an Initial Inspection Test Point (ITP) Procedure, to verify that the gloves were in a good condition prior to beginning the test. The test itself consisted of 50 test sessions, each containing two sets of cycling scenarios with each hand. A single cycling scenario is defined in Table 4.

Quick Look Inspections were performed after every two test sessions to document the condition of the gloves, and more detailed Interim ITPs were performed once after every eight test sessions. The Test Sequence Data Table, Table 8.2 in the ETDP Phase VI Glove Durability Test Plan³, contains the complete sequence of events that were performed in the test. Detailed procedures for each event listed in the Test Sequence Data Table were included as

Table 4. Single cycling scenario.

| Task | # Times per Right Hand | # Times per Left Hand |
|-----------------------------|------------------------|-----------------------|
| Fluid Connector Mate/Demate | 30 | 30 |
| Joystick Cycle | 30 | 30 |
| Rock Pick-up | 32 | 32 |
| Brush Task (10x)* | 54 | 54 |
| Hammer Task (5x) | 20 | 20 |
| Scoop Task | 24 | 24 |
| Rake Task (10x) | 16 | 16 |
| 2-Hand Carry Task | 20 | 0** |

*Unless denoted otherwise, one iteration of each task was considered as a single task.

**The 2-Hand Carry Task is performed with 2 hands

B. Test Location

The first 18 test sessions were performed in the ABF, in order to allow for the collection of motion capture and force data. At the conclusion of 18 test sessions, the test team decided that a sufficient amount of motion capture data had been collected. The Vicon® motion capture markers were removed from the gloves, the instrumentation was removed from the tools, and the remainder of the test sessions were held in the Building 7 Blue Room.

C. Allowable Maintenance

The following items were considered allowable types of maintenance during the testing:

1. Minor cleaning of the Phase VI Gloves, such as using standard cleaning procedures to clean the inside of the glove bladder or wiping the seals with lubricant.
2. Since the Glove Thermal Micrometeoroid Garment (TMG) is an On-orbit Replacement Unit (ORU) component, repair of any unsatisfactory condition with the TMG was allowed at any time provided that the repair was included in the Glove Damage Log.
3. Upon glove failure, as described in the Phase VI Glove Failure Criteria, before all cycling sessions were complete, the test was set up to allow for one extensive repair of the gloves. This repair, if needed was to include examination and determination of the cause of glove failure, brainstorming of repair methods by the test team, downselect to a single repair method, and repair of the gloves.

Maintenance type #1, minor cleaning of the gloves, was the only maintenance actually performed during testing.

D. Phase VI Glove Failure Criteria

During testing, the Phase VI gloves were necessarily put into a state of increased risk for failure. Careful and frequent monitoring by qualified personnel assessed the need for test termination due to glove failure. For this test, a Phase VI Glove failure case was defined as occurring when one or more of the below conditions was detected:

1. Leakage in a single glove beyond 8.0 SCC/M
2. An audible leak in the glove
3. A visible hole in the bladder.
4. A hole or windowing in the restraint beyond an acceptable limit.

appendices to the test plan. Test Data Sheets were filled out during each test session to keep track of the glove cycles.

The test was designed to target wrist flexion/extension, wrist adduction/abduction and finger flexion/extension cycles because these cycles make use of the primary glove mobility joints. Additionally, past Phase VI glove cycle testing has targeted and tracked these same motions. Table 5 describes the cycles planned per test session, the total cycles planned over the course of the test, and the goal cycles (i.e. cycles required over a 6 month lunar outpost mission with a FOS of 2). The goal cycles were taken from the Final Cycle Model (Table 3). As seen below, the test plan contained 550 less wrist flexion/extension cycles than the goal value, 91 less wrist adduction/abduction cycles than the goal value, and 561 more finger flexion/extension cycles than the goal value. In all three cases, the total cycles were off from the goal cycles by less than 1 percent, which was considered negligible when looking at the large number of cycles.

Table 5. Summary of test cycles.

| Glove Motion | Cycles per Test Session | Total Cycles per Test Plan | Goal Cycles |
|---------------------------|-------------------------|----------------------------|-------------|
| Wrist Flexion/Extension | 1659 | 82,962 | 83,512 |
| Wrist Adduction/Abduction | 3406 | 170,298 | 170,389 |
| Finger | 678 | 33,888 | 33,327 |

The acceptable restraint hole size was not defined in the test plan, and was left as a judgment call made by the suit engineer and test conductor. As will be described in more detail in the results section of this paper, no failures occurred during testing.

V. Test Hardware Description

A. Phase VI Gloves

A single pair of Phase VI gloves, Size 6LA, was used as the test article during this test. The gloves were pressurized to 4.3 psid during each test session. Both gloves were tested in a ‘dirty’ configuration. To achieve this ‘dirty’ configuration, 2 oz. of JSC-1 lunar simulant was inserted between the TMG and bladder/restraint assembly of each glove prior to the start of testing, the gloves were shaken to attempt to apply an even coat of simulant to the restraint layer, and the excess simulant was dumped out of the glove assemblies. The gloves were weighed before and after adding the simulant, to determine the weight of simulant coating the inside of the gloves. At the completion of the simulant insertion, the right Phase VI glove contained 0.32 oz. of JSC-1 simulant, and the left Phase VI glove contained 0.64 oz. of JSC-1 simulant.

According to the Phase VI Glove Certification Test Plan⁴, it had been demonstrated in previous glove cycle tests that the finger length adjustment had little or no effect on glove degradation. Therefore, the gloves were sized throughout the test to maximize suit subject comfort. This was considered a realistic approach to testing since a crew member would normally not train or fly in an ill-fitting glove. Spectra® comfort gloves and wristlets were worn beneath the Phase VI gloves by the suit subjects during all phases of manned cycling.

As shown in Fig. 1, Velcro® backing pieces were sewn onto specific locations on both the left and right gloves to affix retro-reflective markers for the collection of motion capture data.



Figure 1. Phase VI gloves with retro-reflective markers attached.



Figure 2. EMU with polypropylene gauntlets and dust bib installed.

B. Extravehicular Mobility Unit

The Space Shuttle Program (SSP) Extravehicular Mobility Unit (EMU) was worn by test subjects throughout the duration of testing. The suit was pressurized to 4.3 psid. The suit hard upper torso (HUT) was affixed to the EMU load relief system, to relieve the subject of bearing the full suit weight during testing.

Polypropylene gauntlets were worn on both EMU lower arms to prevent any simulant that migrated out of the gloves from contaminating other components of the EMU. Additionally, all subjects wore a dust bib across their chest while suited, as shown in Fig. 2, to keep from contaminating the EMU with dust.

D. Glove Task Busy-board

A busy-board (Fig. 3), fabricated in the Advanced Suit Laboratory (ASL) at the Johnson Space Center (JSC), was used by the subjects to complete all required tasks. The busy-board height was adjustable, to accommodate different sized subjects. Additionally, the upper portion of the busy-board, containing the majority of the tools, was able to rotate, allowing the subjects to remain stationary throughout the test.

The tools used in this study were representative of tools that would be used during EVA tasks, and included a shovel, hammer, and dust brush, which were borrowed from the EVA Tools and Equipment Branch.

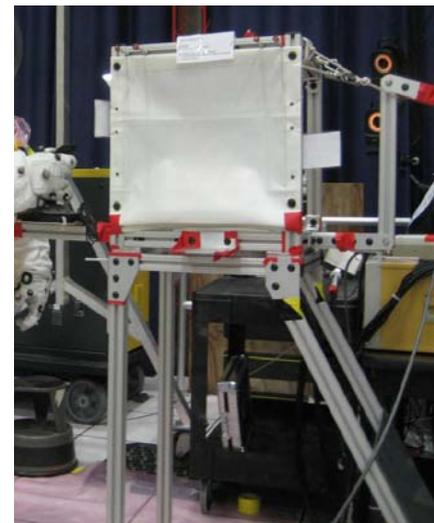


Figure 3. Glove durability test task busy-board.

The shovel, hammer, and brush handles were hollowed out and instrumented with small load cells to capture the grip forces (compression) during the tasks, as shown in Fig. 4. Figure 5 shows the hammer, shovel and brush in use during testing.

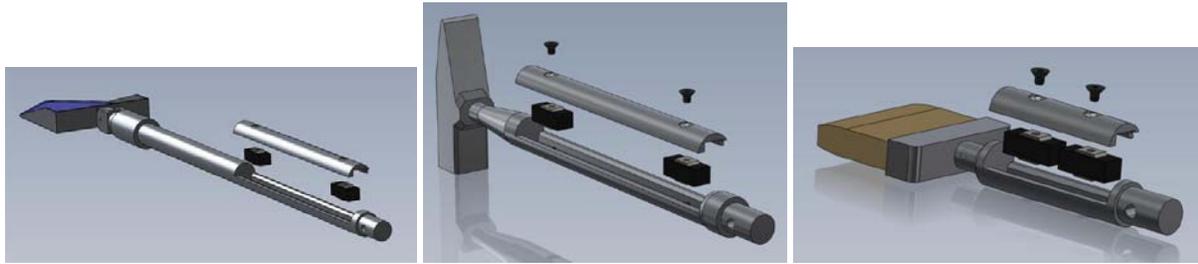


Figure 4. Instrumented shovel (left), hammer (center) and brush (right) with load cells incorporated.



Figure 5. Subjects performing hammer (left), scoop (center) and brush (right) tasks.

In addition to these three tools, a mock-up was created to represent a two-handed grab task (i.e. lifting a rock box or suit port transfer module). The two-handed grab mock-up was instrumented with a 6-axis load cell to collect the push-pull forces (compression and shear) during the tasks. The load cell was attached directly behind the handrails as shown in Fig. 6. The other remaining tools included a fluid connector, a commercial-off-the-shelf (COTS) joystick, and a rock sample (Fig. 7). These tools were not instrumented with load cells due to difficulty in housing the load cells.



Figure 6. Subject using the 2-handed grab mock-up with load cell circled in red.

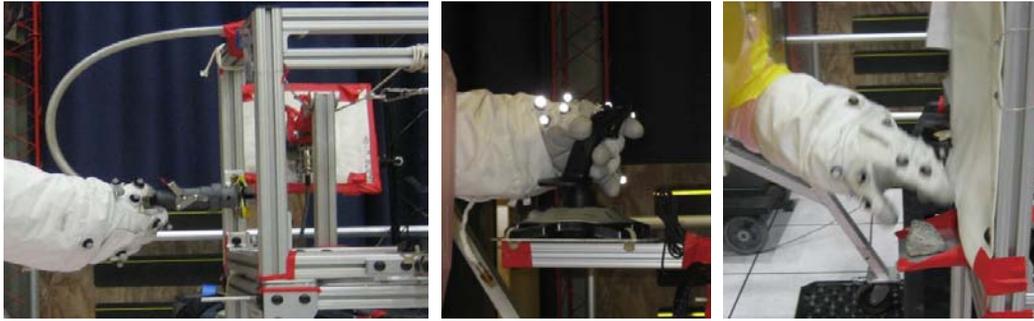


Figure 7. Subjects performing fluid connector (left), joystick (center) and rock pick-up (right) tasks.

E. Motion and Force Capture System

The ABF Vicon® MX Motion Capture System (digital cameras, Giganet controller board, and DAQ board) was used during the first 18 test sessions to collect a sampling of cycle data. The Vicon® system uses a system of digital video cameras with a ring of IR LEDs around each lens. The light from these LEDs reflects off of small retro-reflective markers which the cameras see and record. Software included with the Vicon® system processes the data stream from each camera and triangulates the position of each marker in 3D space. The software used during testing included the following: Vicon® Nexus (version 1.3) to collect data, Vicon® Bodybuilder (version 3.6) to calculate the inverse kinematics, and MATLAB (version R2010a) to do the analysis. Figures 8 and 9 show the Vicon® cameras and camera set-up used during testing.



Figure 8. The Vicon® MX T40 camera.

The compression load cells used for the instrumented handles were the Transducer Techniques® MLP-50 (50 lbs max) for the brush handle and MLP-100 (100 lbs max) for the hammer and shovel handles. The 6-axis load cell was an Advanced Material Technology, Inc. (AMTI) MC3-6 (1000 lbs max). A Vishay® Strain Gage Signal Conditioner/Amplifier was used to condition the load cells.

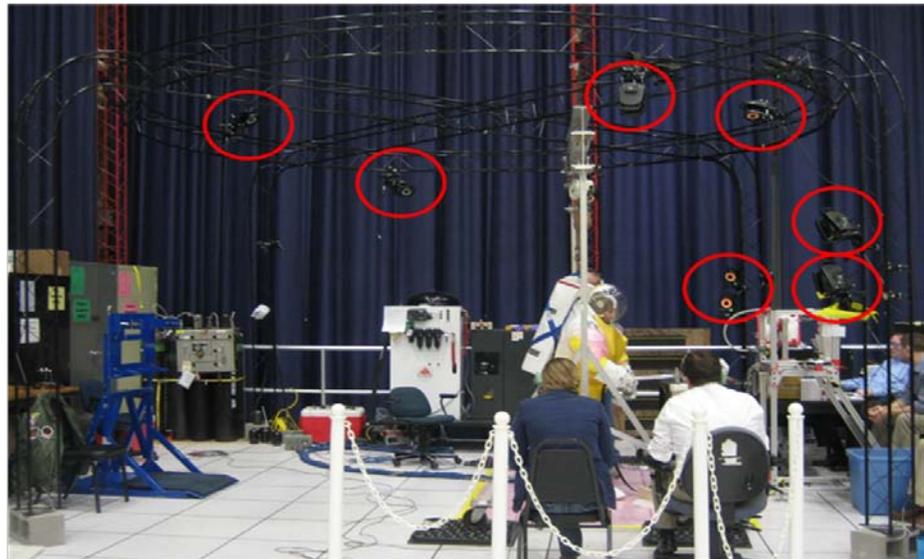


Figure 9. Vicon® camera setup on frame in ABF.

VI. Test Results

A. Summary of Results

All 50 test sessions were completed without failure of the gloves. Per the defined failure criteria, this means that the glove leakage remained within specifications (below 8.0 SCC/M), and no audible leaks or visible holes were found on the glove bladders. Additionally, no unacceptable holes or windowing were observed on the glove restraints. The majority of observed damaged occurred on the glove TMGs, which experienced wear on the room temperature vulcanized rubber (RTV) and holes in the palm area. The main area of wear on the glove restraints was fraying of the palm bar webbing, which led to the eventual exposure of the palm bar, but no structural damage to the

gloves. The glove wear is described in Section B of the Test Results. Results of the motion capture and force data collection are described in detail in Section C of the Test Results.

B. Results of Visual Inspections

As described in the test overview section of the report, ITPs were performed after every 8 test sessions. A total of 7 ITPs were performed throughout testing, including an initial ITP, 5 interim ITPs, and a final ITP. During each ITP, comments were recorded on the condition of the various glove components.

The first component of the glove that was examined during each ITP was the exterior side of the TMG. The main areas of wear on the right exterior TMG included a hole in the RTV at the base of the thumb cap, which first appeared at ITP #3, and gradually grew throughout the testing. In addition to this hole, slices were noticed in the RTV outboard of index finger on the palm pad, and the RTV began to wear off of the thumb finger cap beginning at ITP #3. Photos of the right exterior TMG condition at the final ITP are included as Fig. 10 and 11 below.



Figure 10. Palm side of right exterior TMG at final ITP.



Figure 11. Close up photos of right exterior TMG at final ITP: palm bar (left), slices in RTV outboard of index finger (center), RTV missing at base of thumb pad (right).

The main areas of wear on the left exterior TMG were similar to those on the right TMG, and included a hole in the Vectran® at the base of the thumb cap, which first appeared at ITP #2, and gradually grew throughout the testing. While the hole in the left TMG appeared before the hole in the right TMG, it was slightly smaller than the right TMG hole at the end of testing. In addition to the hole between the thumb ball and palm pad, a small hole was observed on the ring finger little finger side during ITP #4. It was later discovered that this hole was caused by the incorrect performance of the fluid connector task by one of the test subjects. The subject's motion was corrected, and the hole size remained the same throughout the remainder of testing. Photos of the left exterior TMG condition at the final ITP are included as Fig. 12 and 13 below.



Figure 12. Palm side of left exterior TMG at final ITP.



Figure 13. Close up photos of left exterior TMG at final ITP: palm bar (left), abrasion on index side of middle finger (right).

The second component of the glove examined during each ITP was the interior side of the TMG. The main area of wear on the right interior TMG included the RTV hole at the base of the thumb cap as seen on the outer TMG. Additional wear included tearing and delamination of the Mylar tape, as well as pulling away of the butterfly insulation of the thumb. Photos of the right interior TMG condition at the final ITP are included as Fig. 14 below.



Figure 14. Photos of right interior TMG at final ITP: hole on palm bar (left), damaged butterfly tape on thumb (right).

The main area of wear on the left interior TMG was the RTV hole at the base of the thumb cap as seen on the outer TMG. Additional wear was similar to what was seen on the right interior TMG, including tearing and peeling away of the Mylar tape, as well as damage to the butterfly insulation on all fingertips. Photos of the left interior TMG condition at the final ITP are included as Fig. 15 below.



Figure 15. Photos of left interior TMG at final ITP: overall condition (left), damaged butterfly tape on fingers (right).

The next area of the glove examined for wear was the outer restraint. The major areas of wear on the right restraint included fraying and eventual wear through of the webbing on the palm bar, below the hole on the TMG and abrasion/wear on the second lowest thumb gore. At the conclusion of testing, the bladder was visible through the restraint layer due to the wear on the thumb gore, and due to abrasion on the lowest middle finger gore. Photos of the right restraint condition at the final ITP are included as Fig. 16 and 17 below.

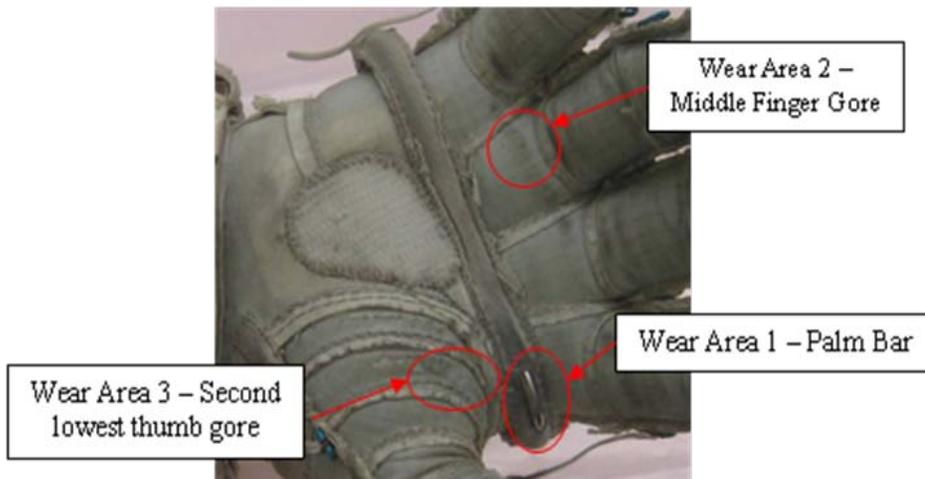


Figure 16. Right exterior restraint areas of wear at final ITP.



Figure 17. Close-up photos of right exterior restraint areas of wear at final ITP: wear area 1 (left), wear area 2 (center), wear area 3 (right).

The major areas of wear on the left restraint were identical to those on the right restraint, and included abrasion and eventual wear through of the webbing on the palm bar and thinning of the restraint material on the second lowest thumb gore. Photos of the left restraint condition at the final ITP are included as Fig. 18 and 19 below.



Figure 18. Left exterior restraint areas of wear at final ITP.



Figure 19. Close-up photos of left exterior restraint areas of wear at final ITP: wear area 1 (left), wear area 2 (right).

During ITPs #1-5, the gloves were left assembled, making it very difficult to see the condition of the inner restraint and the inner or outer bladder. Therefore, very few notes on the inner restraint and inner bladder conditions were taken, and no notes on the outer bladder were taken. The gloves were de-integrated during the final ITP (ITP #6), and more detailed notes were recorded on the final condition. Dust migration primarily occurred at the seams of the gloves along the fingers and fingertips. No additional abrasion was found beyond what was observed on the outer side of the glove restraints. No abrasion was noted on either bladder. One interesting observation was that the majority of simulant which migrated through the glove outer layers became stuck to the anchor tape on the glove fingertips and fingers, as seen in Fig. 20.



Figure 20. Palm side of left exterior TMG at final ITP.

C. Results of Motion Capture and Force Data Collection

In addition to baselining the durability of the gloves, this testing also aimed to verify the accuracy of the pilot test data and cycle model table through the collection of motion capture and force data during testing. As described in the Test Plan Overview Section, motion capture and force data were collected by the ABF for the first 18 test sessions. This section specifically looks at a comparison of the motion capture data obtained during testing to the data obtained during the pilot test. The ABF Glove Durability Test Report¹, presents a detailed look at the motion capture and force data collected during testing. The ABF report can be referenced for a summary of the force collection results, as well as more detailed information on the motion capture process and results.

As mentioned above, the data used in this section was taken from 18 test sessions. During these 18 test sessions, 8 different test subjects were used. The subject demographics for the sessions in which motion capture and force data was collected are described in Table 6. As noted in Table 6, 3/4 of the subjects were right handed, approximately 2/3 were male, and the same percentage of subjects had what was considered a good glove fit.

Table 6. Subject demographics for data collection test sessions.

| | Male | Good Glove Fit | Right Handed |
|-------------------------------------|------|----------------|--------------|
| Percentage of total subjects | 63% | 63% | 75% |

Table 7 compares the wrist flexion/extension and wrist adduction/abduction data for the pilot and actual testing, and Table 8 compares the thumb, index, pinky and average finger flexion/extension cycles for the pilot and actual testing. The pilot test numbers listed in the tables are the average cycle numbers of both hands of 6 different test subjects during pilot testing. The actual test numbers listed in the tables are the average cycle numbers of both hands of the 8 test subjects during suited, pressurized testing. Unless denoted otherwise, the cycle values are for one repetition of the task. The two handed grab task was performed differently in the actual testing than it was in the pilot testing (i.e. as two separate tasks rather than one), and therefore, the numbers are not directly comparable between the two scenarios, and are provided for reference only.

Table 7. Wrist flexion/extension and adduction/abduction cycles for pilot and actual testing.

| Task # | Task | Wrist Flex/Ext | | | Wrist Add/Abd | | |
|--------|------------------|----------------|-------------|------------|---------------|-------------|------------|
| | | Pilot Test | Actual Test | Difference | Pilot Test | Actual Test | Difference |
| 1 | Fluid Connector | 1.58 | 4 | 2.42 | 4.04 | 3.4 | -0.64 |
| 2 | Rock Pick-up | 2.06 | 1.4 | -0.66 | 1.88 | 1.2 | -0.68 |
| 3 | Joystick | 1.63 | 2.9 | 1.27 | 4.33 | 2.9 | -1.43 |
| 4 | Hammer (5x) | 2.75 | 3.1 | 0.35 | 5.75 | 2.7 | -3.05 |
| 5 | Brush (10x) | 7.7 | 4.2 | -3.5 | 17.7 | 6.2 | -11.5 |
| 6 | Scoop | 1.7 | 2.3 | 0.6 | 2.68 | 2.7 | 0.02 |
| 7 | Rake (10x) | 9.3 | 5.7 | -3.6 | 13.3 | 5.1 | -8.2 |
| 8 | Two Handed Grab | 0.35 | N/A | N/A | 2.19 | N/A | N/A |
| 8a | Two Handed Grasp | N/A | 0.6 | N/A | N/A | 1.1 | N/A |
| 8b | Two Handed Move | N/A | 1.5 | N/A | N/A | 1.6 | N/A |

Areas in which the number of cycles increased in the actual testing over what was recorded in the pilot testing are highlighted in blue in Table 7. Areas in which the number of cycles decreased in the actual testing are highlighted in yellow. As seen above, some variation existed between the pilot test and actual test for all tasks, and quite a bit of variation existed for some tasks. Looking specifically at the wrist flexion/extension cycles, the average number of cycles increased in the actual test for about half the tasks, and decreased for the other tasks. While intuition would suggest that the number of cycles would decrease during pressurized testing due to the increased stiffness of the gloves when pressurized, it was observed that this same stiffness at times caused subjects to struggle more with tasks, and thus, cycle the gloves more than in the pilot test. Looking at the wrist adduction/abduction cycles, almost all tasks had a decrease in cycles during the pressurized testing, which aligns with the expected result.

Table 8. Finger flexion/extension cycles for pilot and actual testing.

| Task # | Task | Thumb Flex/Ext | | | Index Flex/Ext | | | Pinky Flex/Ext | | | Finger Flex/Ext | | |
|--------|------------------|----------------|-------------|------|----------------|-------------|------|----------------|-------------|------|-----------------|-------------|------|
| | | Pilot Test | Actual Test | Diff | Pilot Test | Actual Test | Diff | Pilot Test | Actual Test | Diff | Pilot Test | Actual Test | Diff |
| 1 | Fluid Connector | 2.52 | 4.1 | 1.58 | 1.62 | 4.4 | 2.78 | 2.28 | 4.1 | 1.82 | 2.14 | 4.20 | 2.06 |
| 2 | Rock Pick-up | 1.03 | 1.8 | 0.77 | 0.82 | 2.6 | 1.78 | 1.27 | 1.8 | 0.53 | 1.04 | 2.07 | 1.03 |
| 3 | Joystick | 1.5 | 1.8 | 0.3 | 0.43 | 3.3 | 2.87 | 0.27 | 2.1 | 1.83 | 0.73 | 2.40 | 1.67 |
| 4 | Hammer (5x) | 1.52 | 2.9 | 1.38 | 1.33 | 1.9 | 0.57 | 1.67 | 1.7 | 0.03 | 1.51 | 2.17 | 0.66 |
| 5 | Brush (10x) | 2.33 | 4.9 | 2.57 | 1.4 | 2.9 | 1.5 | 1.83 | 3.5 | 1.67 | 1.85 | 3.77 | 1.91 |
| 6 | Scoop | 2.54 | 3.8 | 1.26 | 0.92 | 3.4 | 2.48 | 1.89 | 1.9 | 0.01 | 1.78 | 3.03 | 1.25 |
| 7 | Rake (10x) | 1.43 | 4.8 | 3.37 | 1.6 | 5.8 | 4.2 | 1.87 | 2.4 | 0.53 | 1.63 | 4.33 | 2.70 |
| 8 | Two Handed Grab | 1.45 | N/A | N/A | 0.55 | N/A | N/A | 1.1 | N/A | N/A | 1.03 | N/A | N/A |
| 8a | Two Handed Grasp | N/A | 1.3 | N/A | N/A | 1.5 | N/A | N/A | 1.2 | N/A | N/A | 1.33 | N/A |
| 8b | Two Handed Move | N/A | 1 | N/A | N/A | 1.6 | N/A | N/A | 1.4 | N/A | N/A | 1.33 | N/A |

As seen in the finger flexion/extension table, the number of cycles increased for all tasks in the actual testing over what was recorded in the pilot testing (difference between pilot and actual testing highlighted in blue). While yet again, this result may be counterintuitive, the increased cycles were likely caused by a combination of subjects struggling more with tasks while pressurized, and in the tasks which involved several iterations of a task such as hammering, slight release and re-grip of the tools in between iterations.

In addition to the results of the pilot and actual testing differing due to the increased stiffness of the gloves when pressurized and the increased difficulty in performing tasks while pressurized, other factors which likely contributed to the difference in results include overall glove fit, hand dominance, test subject fatigue as the test session progressed, and the fact that subjects were fully suited during the actual testing, while they only wore gloves during the pilot test.

Expanded tables including both hand and glove fit are provided in Appendices B through E of the ABF Glove Durability Test Report¹. There were noticeable differences between the wrist, thumb, and index finger motions between subjects with good and poor fit, but the differences were inconsistent across the tasks.

VII. Conclusions and Recommended Forward Work

The results of visual inspections showed that the TMGs are the main area in which glove durability improvements are needed. Since the majority of the TMG damage was experienced directly over the palm bar, this portion of the glove warrants the most improvement.

Aside from the TMG damage, the gloves sustained less damage than was originally anticipated. While the test was designed to be representative of the cycles seen over a 6 month mission, it is possible that flaws in the simulant fidelity and/or test protocol led to less wear than what would be seen during 6 months of actual EVA on a planetary surface. Several possible flaws in the simulant fidelity and test protocol include the following:

1. The JSC-1 simulant used in this test may not be as abrasive as actual lunar soil, leading to less overall wear, especially on the restraint layer of the gloves.
2. Due to suit contamination concerns, simulant was only inserted between the TMG and restraint layers of the gloves, and no simulant was placed on the tools themselves to represent dust that would be encountered in a planetary environment. Dust external to the TMGs will likely lead to increased TMG wear in a real mission case.
3. Due to difficulty in selecting subjects for such a large number of test sessions, some subjects had a poor glove fit, which kept them from exercising the gloves to the limits of their range of motion, and therefore, the testing was not necessarily representative of worst case cycling.
4. As subjects became fatigued during testing, they tended to ease up on the effort used to perform various tasks. This ease in effort likely led to a reduction in the forces exerted on the gloves, causing them to wear less than they would with worst case forces applied.

As shown by the motion capture results, the motions captured during the pilot testing did not accurately represent the motions used during suited pressurized testing. The varying results between the pilot and actual testing demonstrated that it is not possible to predict suited movement with unpressurized, partially suited testing. It is recommended that future cycle model tables incorporate cycle data from the suited, pressurized testing.

As follow up work from the glove durability testing, a simulant fidelity investigation was completed in early 2011 to investigate the fidelity of JSC-1 simulant when compared to lunar soil, with the objective of determining if flaws in the simulant fidelity may have led to the observation of less wear than expected during testing. The JSC-1 Simulant Fidelity Investigation concluded that while it does not duplicate all the lunar soil properties, “JSC-1 provides an acceptable representation of lunar mare soil for abrasion/wear testing”.⁵ It is therefore more likely that less wear occurred than expected during the glove durability testing due to poor glove fit and/or inconsistency in the forces imparted by subjects on the gloves, than due to the lack of simulant fidelity.

In addition to the forward work already completed, it is recommended to ensure that all subjects used in future cycle tests have a good glove fit, and exert a consistent effort throughout the duration of testing. Prior to future testing, it is also recommended to refine the cycle model table to include pressurized cycle test data.

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IX. References

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⁵Mitchell, Kate, *JSC-1 Simulant Fidelity Investigation*, NASA Report, 2011.

X. Acronyms

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|-------|---|
| AMTI: | Advanced Material Technology, Inc. |
| ASL: | Advanced Suit Laboratory |
| ABF: | Anthropometry and Biomechanics Facility |
| CM: | Crewmember |
| COTS: | Commercial-off-the-Shelf |
| CTSD: | Crew and Thermal Systems Division |
| CxP: | Constellation Program |
| EMU: | Extravehicular Mobility Unit |
| ETDP: | EVA Technology Development Project |
| EVA: | Extravehicular Activity |
| FOS: | Factor of Safety |
| HUT: | Hard Upper Torso |
| ISS: | International Space Station |
| ITP: | Inspection Test Point |
| JSC: | Johnson Space Center |
| ORU: | On-Orbit Replacement Unit |
| RTV: | Room Temperature Vulcanized Rubber |
| SSP: | Space Shuttle Program |
| TMG: | Thermal Micrometeoroid Garment |